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<b>14. ABSTRACT</b> Lack of a reliable blast sensor prevents timely activation of military vehicle occupant safety systems during underbody blasts. Automotive sensors are not suitable. Blast accelerations are larger and occur within shorter time spans. Underbody blasts require a sensor act within 0.5 milliseconds. A Magnetogasdynamics (MGD) sensor was demonstrated to act within 200 microseconds during a 10# TNT equivalent blast. Threshold requirements apply an internally powered sensor to armored personnel carrier type vehicles for timely device activation. The objective requirement uses kinetic energy contained in the blast to activate safety systems. The sensor has unlimited dynamic range, temperature insensitivity, and is survivable within an explosive fireball. Designed as a MGD Tesla rectangular linear motor generator channel with permanent magnets it collects electrons via a blast induced magnetic Alfvén Power Wave. The very small sensor demonstrated harvest potential of 3 Kilowatts and a potentially several Ergs into a matched load. A modification to the sensor connects the ends of the magnets back on each other acting as a combination generator and transformer increasing the voltage and harvest potential to several tens of Kilowatts and Ergs. Harvested power will directly activate occupant safety system's gas generators and explosive actuators.				
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in an Underbody Blast Event – Proposal A131-062-0128 - Contract # W56HZV-13-C-0288



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# Final Scientific and Technical Report Unclassified Contract # W56HZV-13-C-0288 3/7/2014

For the period September 5, 2013 through March 7, 2014

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## Executive Summary

Detonation of explosives underneath a vehicle will apply a large impulse (pressure for a time period) to the underbody in the vertical direction. This is similar to an impact of two bodies but with force concentrated in the vertical direction, a direction not normally occupant protected, especially as it applies to the spine of an occupant.

When the full pressure time impulse is applied to a vehicle underbody momentum is transferred from the pulse to the vehicle causing the vehicle to recoil in a vector direction consisting mostly of an upward vertical component. Due to the difference in masses between the vehicle and pulse and the non-linearity of the load transfer function, time is consumed in the transfer. In the case of impact with another rigid body an accelerometer sensor placed within the occupant area will sense this momentum transfer early enough in time to deploy occupant protective devices such as air bags. However in the case of detonation of a highly energetic explosive, and due to the larger in magnitude and much shorter time span than in an automotive crash or impact event, waiting for an accelerometer response is too late. By the time the accelerometer senses the momentum transfer and deploys protection, the occupant will have experienced a biologically damaging event.

This SBIR tasks the development of a sensor that will detect application of an explosive generated impulse within 500 microseconds after impulse application, defined as  $t(\text{time})=0$ . This is versus the 10 milliseconds or more allotted to a horizontal impact event between two bodies.

This report covers the 6 month Phase I SBIR development of a sensor utilizing Tesla's discoveries and mathematical formulations of the early 20<sup>th</sup> century i.e., the passing of a conductor (in this case an explosive generated gas or shock) through a magnetic field, generating a voltage, and thereby detecting application of an impulse to an underbody of a personnel carrier *prior* to  $t=0$ , thereby allowing sufficient time to deploy personnel protection.

The final conclusions and recommendations as a result of the completed Phase I work are:

- A. The sensor (open circuit voltage output) is linear with the applied magnetic (B) field and input fluid (shock) velocity. (Conclusion)
- B. Measurements of the B Field in a sensor after each application of high shock consistently do not show a change in the B field. Real time scope measurements confirm the B field does not change during fluid (shock transit). This is another statement of linearity. (Conclusion)
- C. The sensor (voltage output) is not a function of conductivity. This is due to the open circuit nature of the measurement. In the quantum limit an open circuit has infinite resistance and therefore requires 1 over infinity conductivity or one electron. (Conclusion)
- D. Based on C above it is recommended that open circuit voltage output be used to detect the events of interest by acting to deploy safety systems when the voltage reaches 4 volts which indicates a Mach Number of 2.85. (Recommendation)

- E. For entry velocities above Mach 1 the signal is positive going with respect to the negative and grounded terminal as determined by the right hand rule. (Conclusion)
- F. The chaos in the fireball does not effect any conclusions, rather works to the advantage of deployment of protective devices by annunciating a biologically damaging event prior to  $t=0$ . (Conclusion)
- G. The sensor measures the first link in the pulse train, thereby sensing an event before  $t=0$ . The sensor delay in signalling an event after application of first impulse is  $\sim 150$  microseconds at  $10\#$  of TNT equivalent for an MRAP vehicle. (Conclusion)
- H. Sensor delay to detection is a function of the particle velocity and decreases linearly as the particle velocity (Mach Number) of the event increases. (Conclusion)
- I. It is unequivocal, as shown in Figure 6.2, that the sensor will detect an event of interest in more than sufficient time to deploy personnel protection. (Conclusion) The full movie of this breakthrough test event has been sent under separate cover to TARDEC, Mr. Sebastian K Karwaczynski.
- J. For this sensor the measured Flux Density is  $\sim 100$  Mwatts/m<sup>2</sup> and internal resistance of an air shock is  $\sim 100$  milliohms. (Conclusion)
- K. Based on J. above it is recommended that the sensor direct drive safety system's gas generators or explosive actuators with event energy. (Recommendation)
- L. The sensor as constructed and demonstrated provides a readily additional benefit of a first alert feature for other military services that will signal or call for help during a damaging event to equipment and/or personnel. It is recommended that consideration be given to utilizing the sensor in this manner. (Recommendation)
- M. The sensor output waveform was demonstrated in Phase I to detect and accurately measure the blast velocity and dynamic pressure in an explosive event. This allows the sensor as constructed and demonstrated to provide the additional benefit of a signal of proper weapon function for target damage assessment applications for Army/Navy indirect fire and Air Force bombing missions. It is recommended that consideration be given to utilizing the sensor in this manner. (Recommendation)
- N. A derivative of the Phase I demonstrated technology could provide next generation hearing protection for combat soldiers, modifying the Phase I sensor by; scaling the geometry of the device to fit the human ear and attaching dropping resistors to harmlessly dissipate the blast energy as heat and protect combat personnel exposed to a shock blast from internal ear damage, but still allowing cognizance of normal sound, and commercially applicable to hunters, fire and police departments as well as Cochlear implant patients. It is recommended that additional investigation be undertaken to determine the feasibility of such a derivative. (Recommendation)



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## Discussion of an Explosive Event

An explosive event burns a solid material producing gases. However in the case of an explosive event the term burning carries a different meaning than thought of when applied to the burning of a common solid material such as wood. The end effects are the same in that both produce gases and heat, but at a highly different rate.

Explosive theory holds that there are two different states in the chemical reaction rate (the rate of change from a solid to a gas) in an explosive material. Deflagration, sometimes called burning, but not to be confused with the burning of everyday material, is a slower event than detonation of solid material by about an order of magnitude. The chemical reaction rate of detonation is in the range of 5 to 10 kilometers per second (Km/sec). This very high reaction rate is the reason a detonated explosive event is so much more energetic than the burning of everyday solids or even deflagration of the material, as kinetic energy goes by the square of the rate or speed of the reaction.

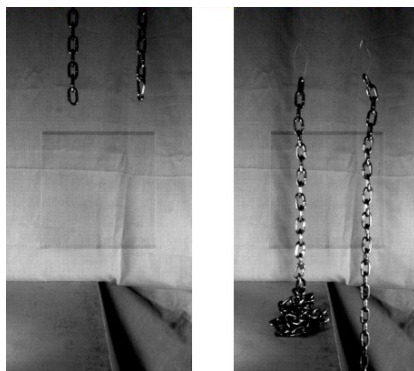
When an explosive detonates it produces a train of impulses of different amplitude pressure and time. If allowed to progress in open air the slower pulses of lower pressure amplitudes are overtaken by the faster pulses of higher pressure amplitudes and constructively interact forming one major event called a **shock** which propagates in the open air media. This is called the far field of an explosive event and occurs outside the visible fireball witnessed in the detonation of explosives. Inside the fireball is called the near field of an explosive event. It is chaotic and defined by many impulses spaced in time with different pressure amplitudes and durations.

In the case of an underbody event the action takes place in the near field as this train of impulses stack up (accumulate) on the intervening underbody forming one main impulse applied to the body and defined as  $t=0$ . The action is best explained with the following analog.

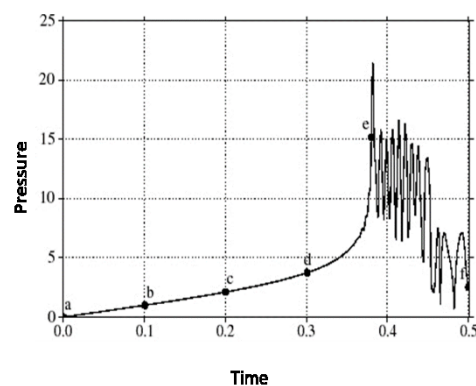
### Chain Analog to Explosive Detonation and -----

#### Chain Falling on a Platform

Each pulse in the near field resulting from the detonation of an explosive is analogous to a chain with different size links falling on a platform. The figure immediately to the right shows the links accumulating on a platform, stacking up, forming one main impulse transferring momentum to the platform body. To the far right is the graph of the event as the links accumulate pressure over time. The area under the curve is the main impulse.



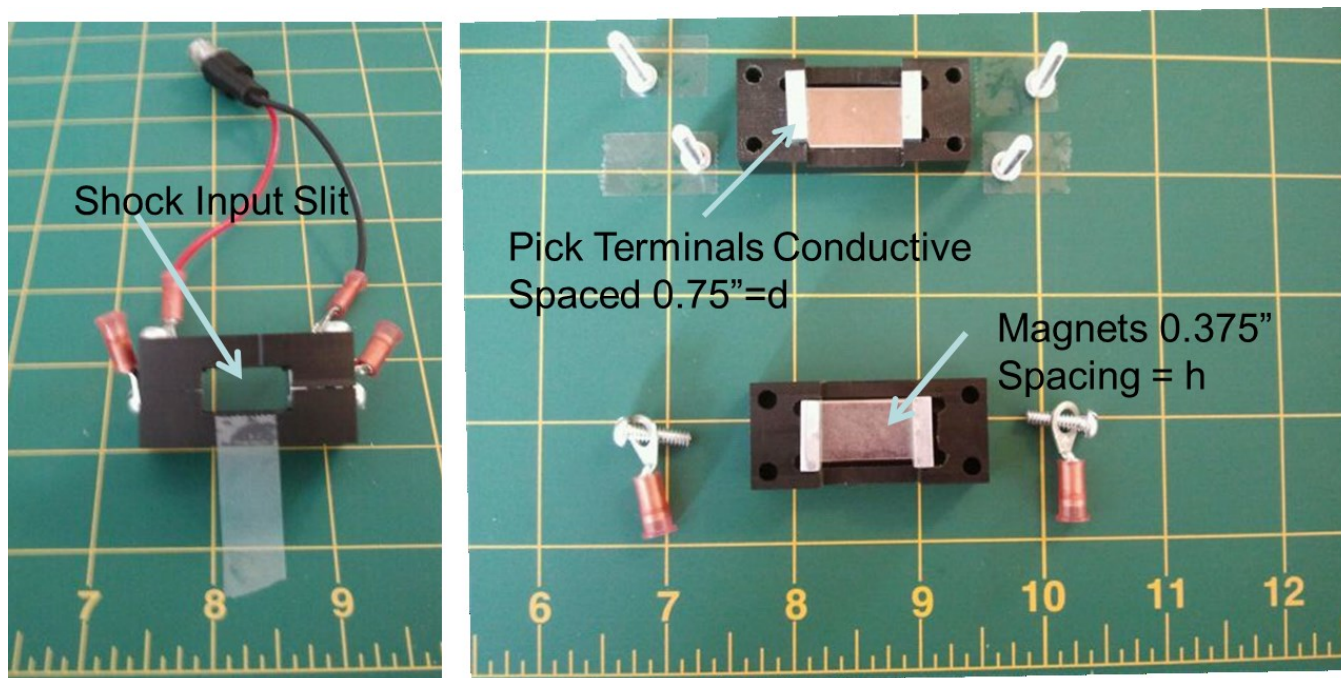
#### IMPULSE ACCUMULATION



## The Proposed Sensor

*This sensor measures the first link; thereby sensing the event prior to  $t=0$ .*

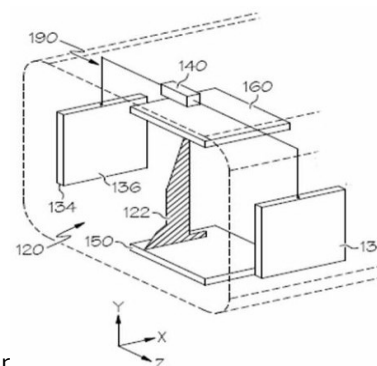
The sensor, shown below is a Magnetogasdynamics (MGD) constant area generator utilizing totally off the shelf components and materials. It works as a Tesla device i.e., a conductor with velocity passing through a magnetic field generates a voltage at the output terminals. It consists of a plastic holder forming a constant area channel, permanent magnets with North Pole facing South Pole and orthogonal conductive pick up terminals that complete the electrical circuit as the fluid (explosive conductive gas products led by a shock that form an individual impulse) passes through the magnetic field. It is analogous to a chain link passing through the channel where the link is in contact with the pickup terminals during its transits through the channel.



**FIGURE 1 Sensor**

The inner workings of the sensor are shown in the figure below:

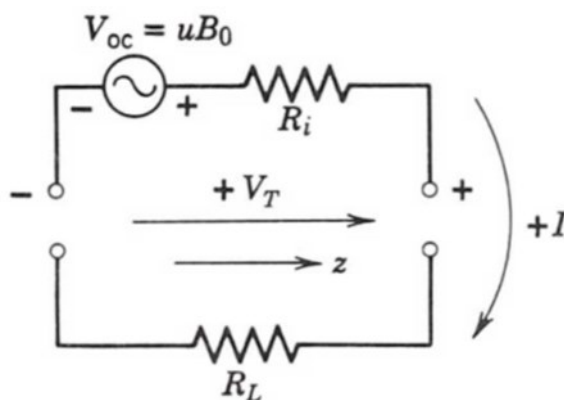
- 120 - One in<sup>3</sup> Sensor
- 122 - Shock Wave
- 130 - Positive Electrode
- 136 - Negative Electrode
- 140 - Voltage Recorder
- 150 - Permanent Magnetic Pole
- 160 - Permanent Magnetic Pole
- 190 - Voltage ( $V_t$ )/Current ( $i$ ) Output



Constant Area MGD Generator

## Sensor Equivalent Electrical Circuit

The electrical equivalent circuit is shown below: Here  $u$  = Velocity of the Fluid (Shock);  $R_i$  = internal resistance of the generator i.e., the fluid item 122;  $V_{oc}$  = the open circuit output voltage;  $V_t$  = terminal voltage;  $R_L$  = load resistance (in the case of open circuit measurement a large resistance);  $I$  = electrical current. The equation  $V_{oc} = uB_0$  is a per unit equation (per meter) and is adjusted for the spacing of pickup terminals in its application as will be shown below.



Sensors (Figure 1) above will be inserted into a receiving antenna array of Figure 2 (analogous to an eyeball) forming the final configuration intended to be mounted to the underbody. Array dimensions: Radius = 2.75"; Height = 1.25".

## Sensor Proposed Receiving Antenna Array

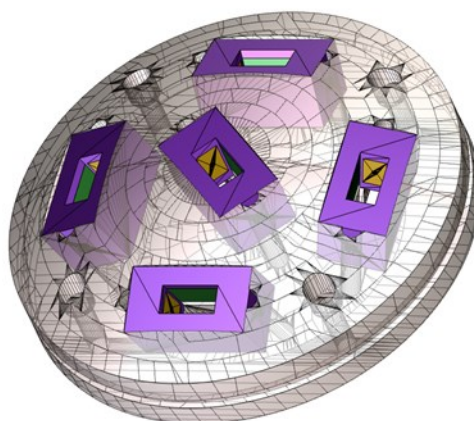


FIGURE 2 Proposed Sensor Receiving Antenna

# First Interim Report

This section is the specific deliverable as specified in Contract W56HZV-13-C-028. It covers the period September 5, 2013 through November 5, 2014 and the following required deliverables:

1. The work performed to date
2. The work performed against the Statement of Work
3. Technical information regarding the sensor i.e., test data results, positive or negative, to include progress against the ultimate goal (a sensor capable of sensing an event early enough to allow personnel protective devices to be deployed); conclusions derived from the data; feasibility and recommendations.
4. Significant changes to the Contractor's organization; contract schedule status; next period activities.

For 1 and 2 above, the work performed to date measured against the contractual tasks is as follows:

There are 9 tasks a thru i as defined in the contract and listed below. Tasks a thru d were completed successfully as individually explained below the tasks.

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## Statement of Work

- a. Define the input required to trigger the protective devices and timing requirements.
- b. Determine the range of lethal shock velocities that an Underbody will be exposed to.
- c. Determine placement of the sensor to intercept the shock prior to interaction with the carriage.
- d. Size the Magnetic B Field, and conductive pick-up terminal spacing to accommodate 1 above.
- e. Design and detail the sensor.
- f. Build prototypes for evaluation testing. Estimate 5 prototypes.
- g. Test prototypes with defined shocks and evaluate the output with Schlieren photography and data recorders. Estimate 10 shock tests to fully characterize an array.
- h. Connect sensor array to protective devices and trigger devices with defined shocks in 2 above.
- i. Prepare the Scientific and Technical Report.

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## Statement of Work Performance

Of the above 9 tasks the first four were completed during the reporting period as follows:

- a. The input required to the protective devices is a trigger level DC signal to a gas generator. The gas generator supplier provides the power circuitry to operate the gas generator. The sensor will provide the **go** signal and present design is a 12 volt amplitude signal at 100 milliamps. Timing requirements are that the **go** signal trigger is to be received no later than 500 microseconds after t=0 (the application to the underbody of the full explosive generated impulse).

- b. The event of interest is the equivalent of 15# of C4 Explosives, either a cased or a bare charge, buried in the ground and a distance of 3 to 4 feet below the underbody. The underbody is an equivalent MRAP weighing 14 Tons. Utilizing the methods of Paul Cooper (Sandia Laboratories) and the computer code CONWEP the velocity at input to the sensor of the fluid (shock) will average MACH 7.5. Due to the chaotic nature of the near field though the range is Mach 4 thru Mach 10. This is a voltage output range of 5.6 volts to 14 volts utilizing the Tesla formulation. This formulation for the specific spacing of pick-up terminals (Figure 1) is  $V = uB_0d$  where  $V$ =open circuit voltage;  $B_0$ =0.225 Tesla;  $d$ =0.75"; and  $u$  the velocity of the input shock (fluid).
- c. Optimally a sensor would be placed in the center of the underbody. However since optimal placement would not necessarily be practical due to geometry constraints or explosive placement a receiving antenna array has been designed to capture the shock (fluid) input from any angle with only a 0.707 ( $\cos 45$ ) drop in the output voltage. The array configuration is shown above in Figure 2. The trigger point is therefore proposed to be set at 4 volts or Mach 2.85 to capture of the first impulse from the event.
- d. The above methodology is near trivial if one assumes, as is the case above, that the Tesla formulation ( $V = uB_0d$ ) is, as it is stated, linear with  $B_0$  and  $u$ , and that voltage output is not a function of ionization (as no term for conductivity appears in Tesla's formulation). The purpose of Task 4 is to make these assumptions unequivocal via empirical data making the sensor setting and detection times a simple matter of applying the Tesla formulation. The subtasks that were completed showing this assumption to be firm are **d1** thru **d4** and are as follows:

## Empirical Data

### **d1. Demonstrate B field linearity and polarity of output.**

The lab test setup is shown below. It consists of a barrel that fires a shotgun primer into a mixed media of Helium and Nitrogen. The mixture is varied to vary velocity.

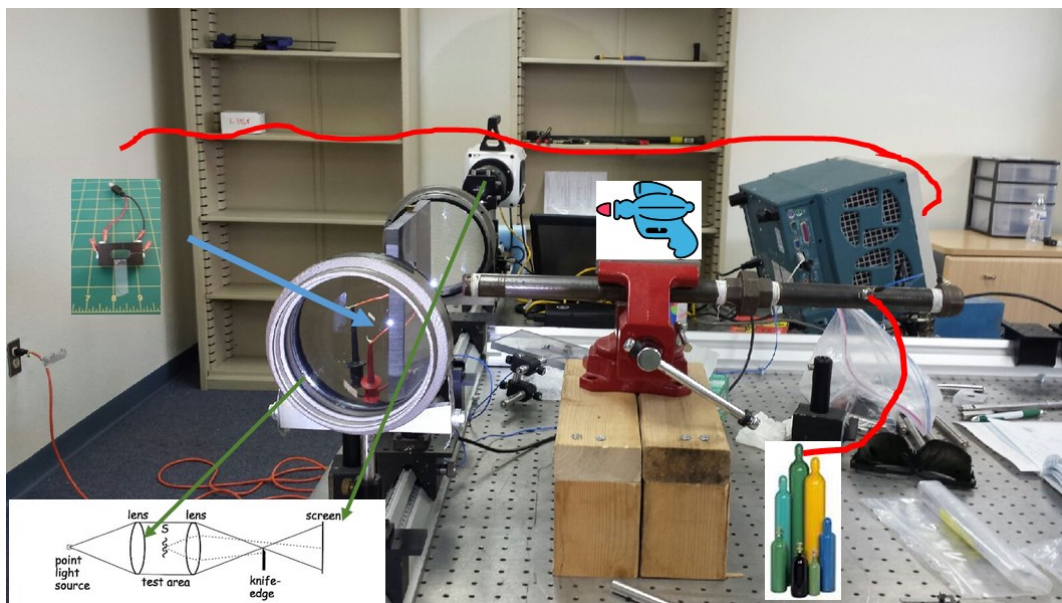
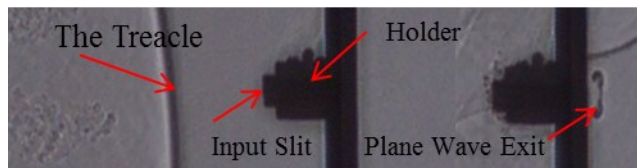


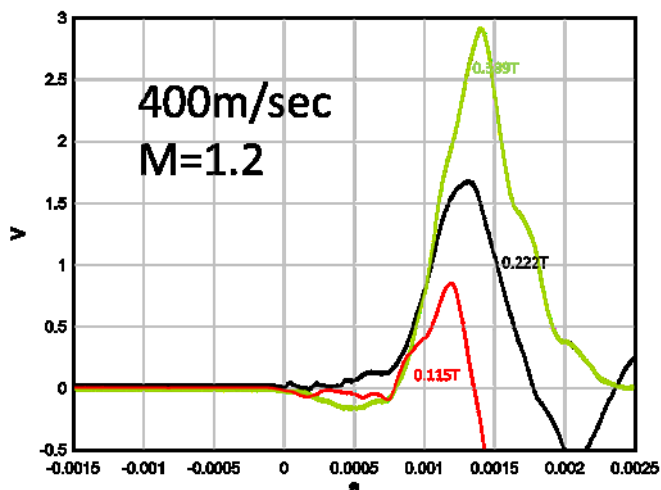
Figure 3-1 Shock Laboratory

Schlieren films (also known as Shadowgraphs that are analogous to filming the visual heat waves rising off a desert floor) are taken for the tests, a sample frame of which is shown below. The Treacle is defined as the mass created by the shock formation which carries the impulse.



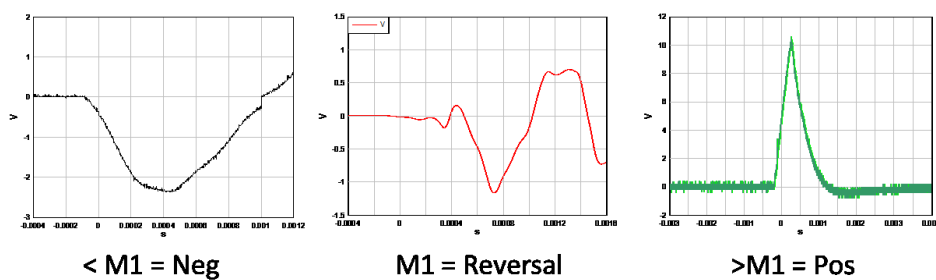
**Figure 4-1 - A Shadow Graph of the Treacle**  
(Dark Area of Shock) impinging  
On a 3/8 x 1/2 x 3/4" MGD  
Constant Area Generator described in Figure 1.

In order to test linearity of the B Field the velocity was held constant while varying the B Field. The results, graphed below, confirm the linearity. B Field amplitude is listed in Teslas next to their respective plot.



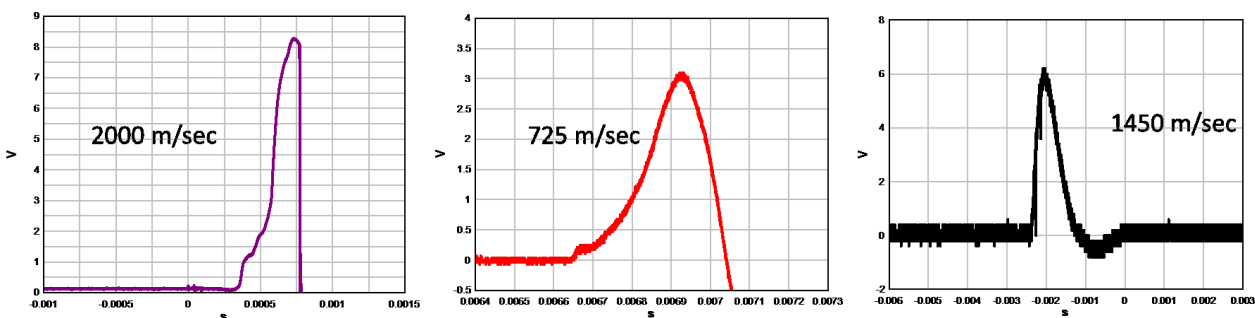
**Figure 5-1 - Varying B field with Velocity held constant**

Theory, not developed until the 60's, holds that a phase reversal occurs at MACH<sub>1</sub>. That is the sign of the output will be different if one operates under MACH<sub>1</sub> then if one operates over MACH<sub>1</sub> by 180 degrees. Our operation is always above MACH<sub>1</sub> so it is import to know the sign of the voltage output with respect to its grounded (zero reference) terminal. As the data below shows operation below MACH<sub>1</sub> is negative and above MACH<sub>1</sub> is positive.



d2. Demonstrate linearity with input shock (fluid) velocity.

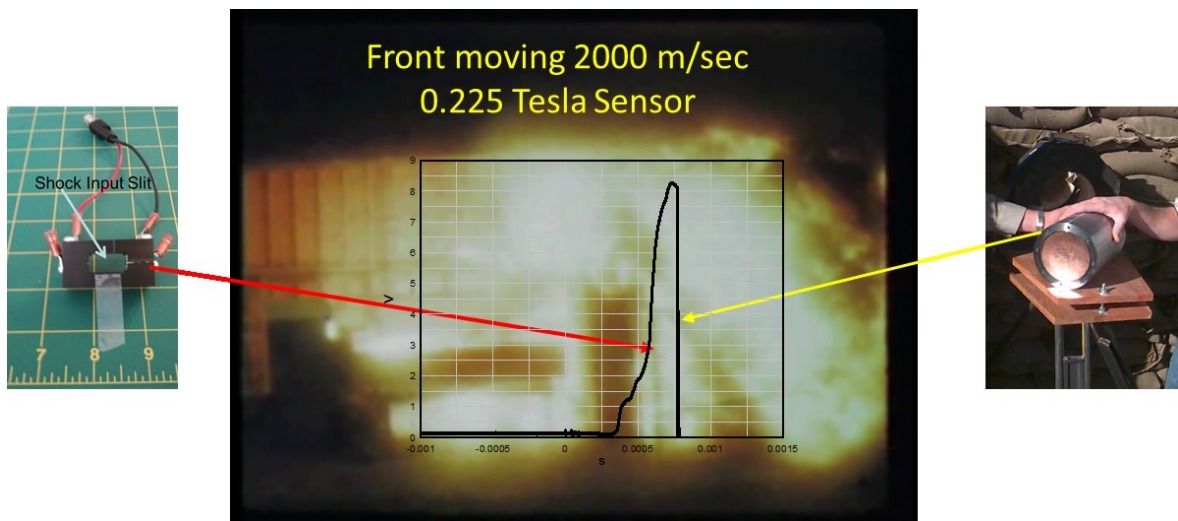
Sensors of Figure 1 above with 0.225 Tesla B fields were subjected to varying shock velocities. The results, shown below, verify linearity with velocity.



d3. Check for B field sensitivity to shock.

While aging of a Neodymium magnet will not cause a reduction in strength they are shock sensitive. However they are only sensitive to very high shocks, shocks that will fracture the magnet. This was confirmed by measuring the Magnetic field before and after each test allowing not only a measurement of their shock resistance but a measurement of resistance to everyday handling. In no case did magnet strength decay due to applied shock in our lab or the handling during test preparation.

D4. Field sensor within a fireball. Demonstrate linear voltage output.



In order to determine near field response of a sensor, sensors were fielded in a 2# cased explosive test. The explosive device (which is an EFP (explosively formed projectile) utilizing LX14 explosives) is shown above to the right, in the center is the output voltage\*time graph of the sensor, and shown to the left of the fireball is the sensor with geometry as in figure 1. In all cases the sensors were demolished or severely damaged, however all tests produced voltages near 10 volts at a distance of 24" from the case, which is the initial impulse chain link.

## Conclusions and Recommendations

For 3 above, the data is presented in purple. From these results the following conclusions and recommendations associated with 3 and for this time period of September 5 through November 5 were:

- A. The sensor (voltage output) is linear with applied B field and input fluid (shock) velocity. (Conclusion)
- B. The sensor (voltage output) is not a function of conductivity. That is, sufficient conductivity exists in an explosive formulation and there are no known explosive formulations that would not contain sufficient ionization to produce linear outputs with B field and velocity. (Conclusion)
- C. For entry velocities above Mach 1 the signal is positive going with respect to the grounded terminal. (Conclusion)
- D. The chaos in the fireball does not effect conclusions A, B, and C above, rather works to the advantage of deployment of protective devices by announcing a biologically damaging event prior to  $t=0$ . (Conclusion)
- E. Measurements of the B Field in a sensor after each application of a shock did not show a change in the B field. Real time scope measurements confirm the B field did not change during fluid (shock transit). This is another statement of linearity. (Conclusion)
- F. The sensor measures the first link in the pulse train, thereby sensing an event before  $t=0$ , indicating the system is feasible and capable of sending a go signal, in sufficient time, to activate personnel protection. (Conclusion)
- G. Based on the above it is recommended that the project:
  - a. Proceed and complete the remaining 5 tasks e thru i.
  - b. Utilize the geometry shown in Figure 1 for the Array Antenna inserts.



- c. Use 1/8" thick magnets with a Tesla rating of 1/4 Tesla.

With respect to 4 above, no significant changes have occurred within H A Consulting or its sub-contractor New Mexico Tech (Energetic Materials Research and Test Center) that would effect the performance of this contract; the contract is on schedule; next interim SOW tasks f and g are planned.

## Second Interim Report

This section is the specific deliverable for the period November 5, 2013 thru January 5, 2014 as specified in Contract W56HZV-13-C-028. It covers the following required deliverables:

1. The work performed to date
2. The work performed against the Statement of Work
3. Technical information regarding the sensor i.e., test data results, positive or negative, to include progress against the ultimate goal (a sensor capable of sensing an event early enough to allow personnel protective devices to be deployed); conclusions derived from the data; feasibility and recommendations.
4. Significant changes to the Contractor's organization; contract schedule status; next period activities.

For 1 and 2 above, the work performed to date measured against the contractual tasks for the stated time period was:

There are 9 tasks a thru i as defined in the contract and listed below. Of the above 9 tasks the first four were completed during the previous 1<sup>st</sup> interim reporting period. Tasks f, and h were completed during this the second reporting period and e was completed thru hardware design and detail while the electrical design and detail portion called the "sensor brain and source stabilization design and detail" is still to be completed. Task g, which also includes a model development, is also partially complete. The completed and partially completed tasks are individually explained below:

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### Statement of Work

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- a. Define the input required to trigger the protective devices and timing requirements.
  - b. Determine the range of lethal shock velocities that an Underbody will be exposed to.
  - c. Determine placement of the sensor to intercept the shock prior to interaction with the carriage.
  - d. Size the Magnetic B Field, and conductive pick-up terminal spacing to accommodate 1 above.
  - e. Design and detail the sensor.
  - f. Build prototypes for evaluation testing. Estimate 5 prototypes.
  - g. Test prototypes with defined shocks and evaluate the output with Schlieren photography and data recorders. Estimate 10 shock tests to fully characterize an array.
  - h. Connect sensor array to protective devices and trigger devices with defined shocks in 2 above.
  - i. Prepare the Scientific and Technical Report.
-

## Statement of Work Performance

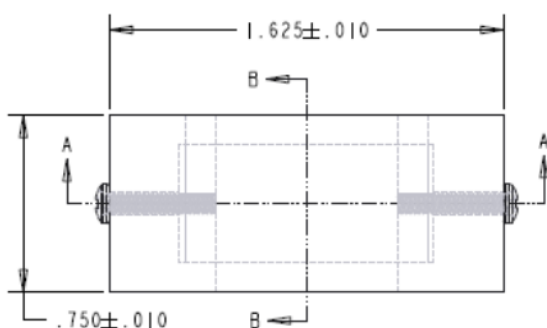
Of the above g tasks the first four were completed during previous 1<sup>st</sup> interim reporting period. Tasks **f**, and **h** were totally completed during this the second reporting period and **e** is 80% complete and **g** is 50% complete as described below:

- e. Once the Tesla formulation ( $V = uB_0d$  where **V**=open circuit voltage; **B<sub>0</sub>**=Magnetic Field in Teslas; **d**=spacing between pickup terminals and **u** the velocity of the input shock fluid) was verified to be linear and not a function of conductivity during the 1<sup>st</sup> interim, the design proceeded. The design parameters were (as determined in the first interim):

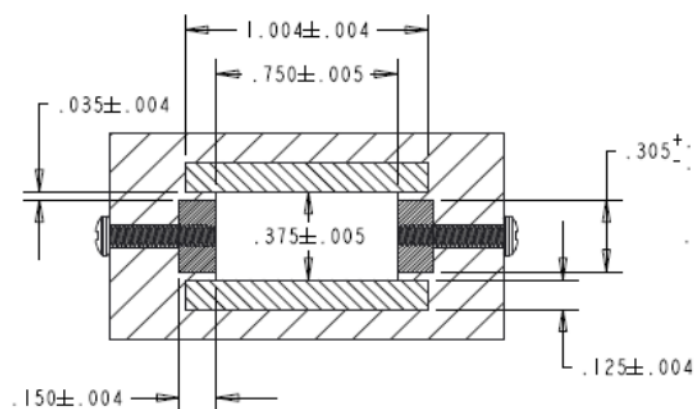
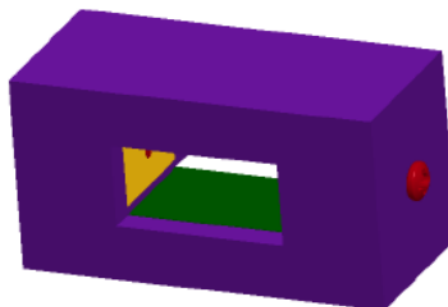
- An input shock velocity of Mach 4 thru Mach 10 which will result in
- A voltage output of 5.6 to 14 volts

The above parameters resulted, as shown designed below, in

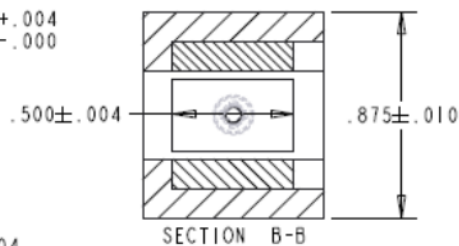
- A **B<sub>0</sub>** field of 0.225 Tesla (which sets the magnet spacing) and
- A distance between electrical voltage pickup plates (**d**) of 0.75".



**SENSOR ASSEMBLY 1/8**



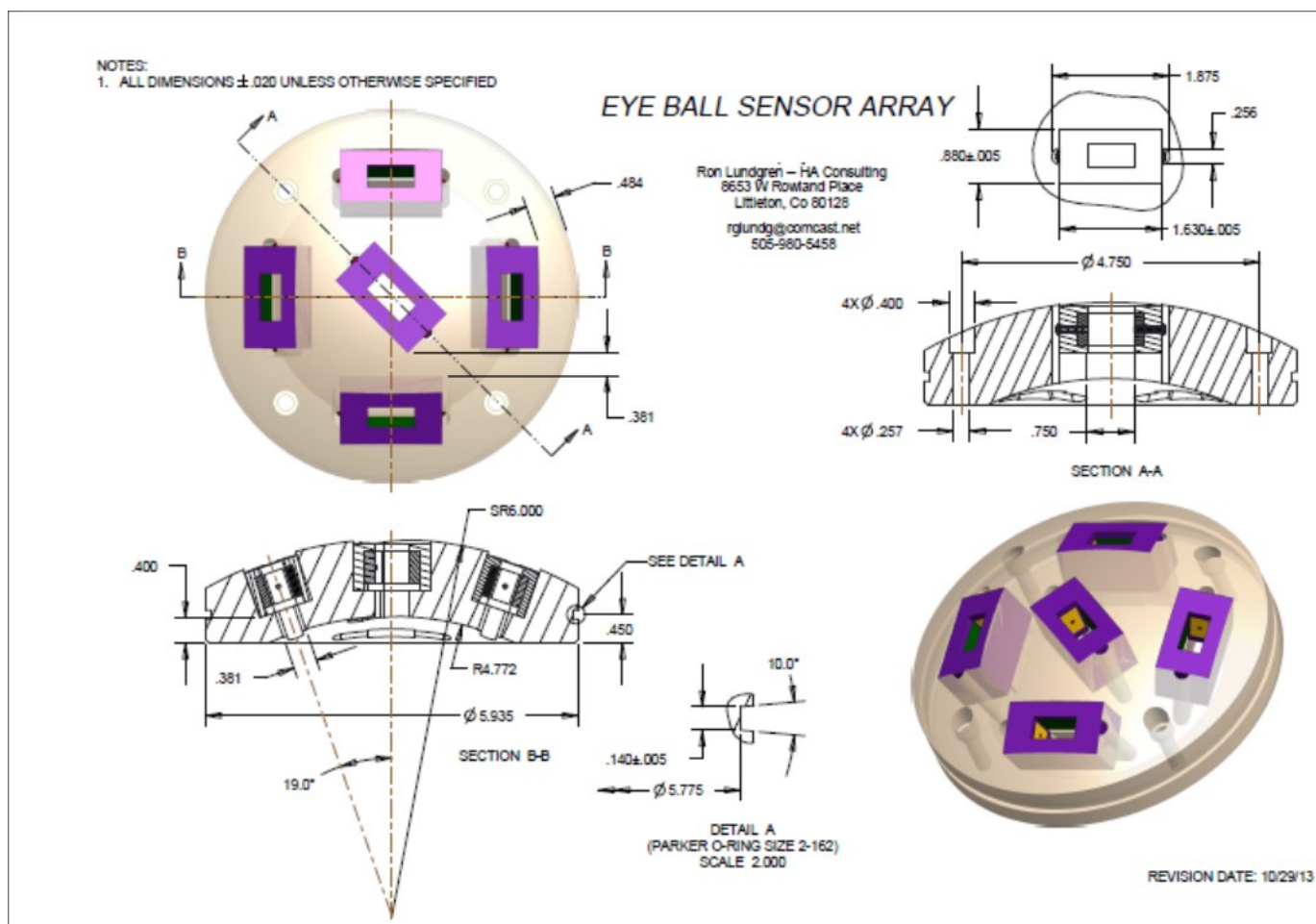
**SECTION A-A**



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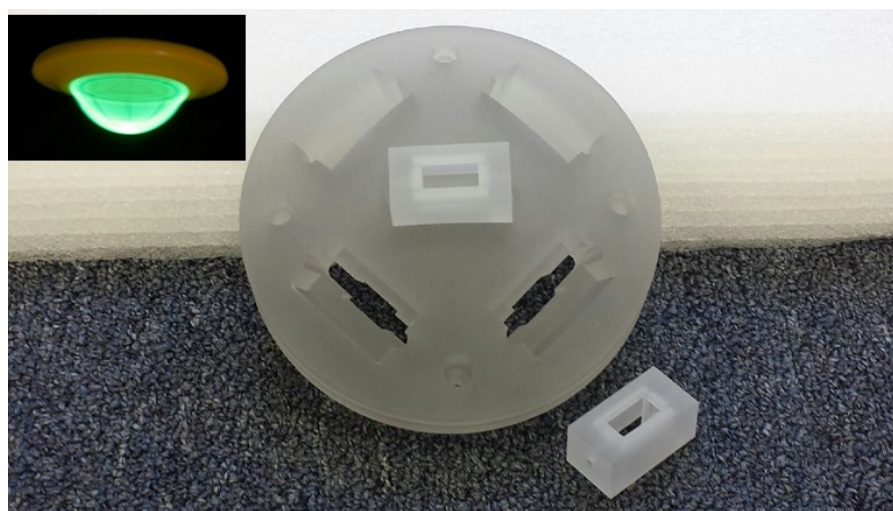
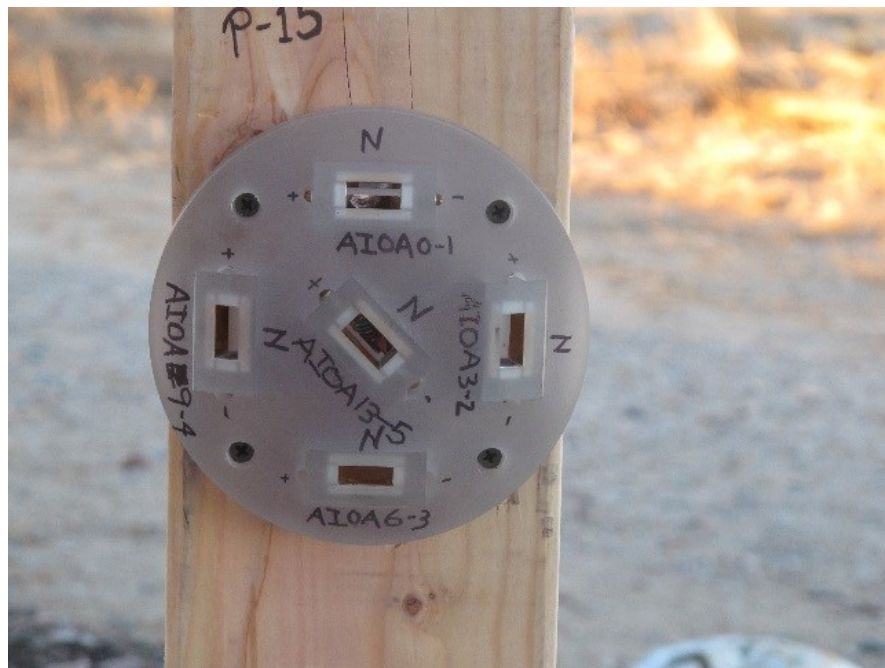
rglundg@comcast.net  
505-980-5458

This in turn was followed by the Array design shown below:



Figures 1-2 Detail Drawings of Sensor and Array

- f. The design prototypes above were built for evaluation testing. These builds are shown below.



*Figure 2-2 Array Components and Installed Array.*

- g. The prototype outputs were fully characterized and tested with defined shocks and the results evaluated with Schlieren photography and data recorders. The results are shown in the Empirical Data section below.

- h. The sensor array was tested at scale 1.5 with the equivalent trigger devices and a defined shock produced by 50#s of C<sub>4</sub> explosive. The results are also shown in the Empirical Data section below.

## Empirical Data

g1. Test prototypes with defined shocks and evaluate the output with Schlieren photography and data recorders.

Before the data is reviewed a system review of the sensor and array technology is presented below. A shock, dragging behind it a Treacle Mass, enters a sensor element of an array and generates a voltage, whose peak is linear with shock velocity. The sensors constant B field delivers a unique Alfvén frequency with unique wave velocity. This allows particle velocity of the shock to also be determined. The voltage is taken as an open circuit voltage to remove any dependency on Treacle conductivity. The voltage generated is utilized by the sensor to detect an event of interest.

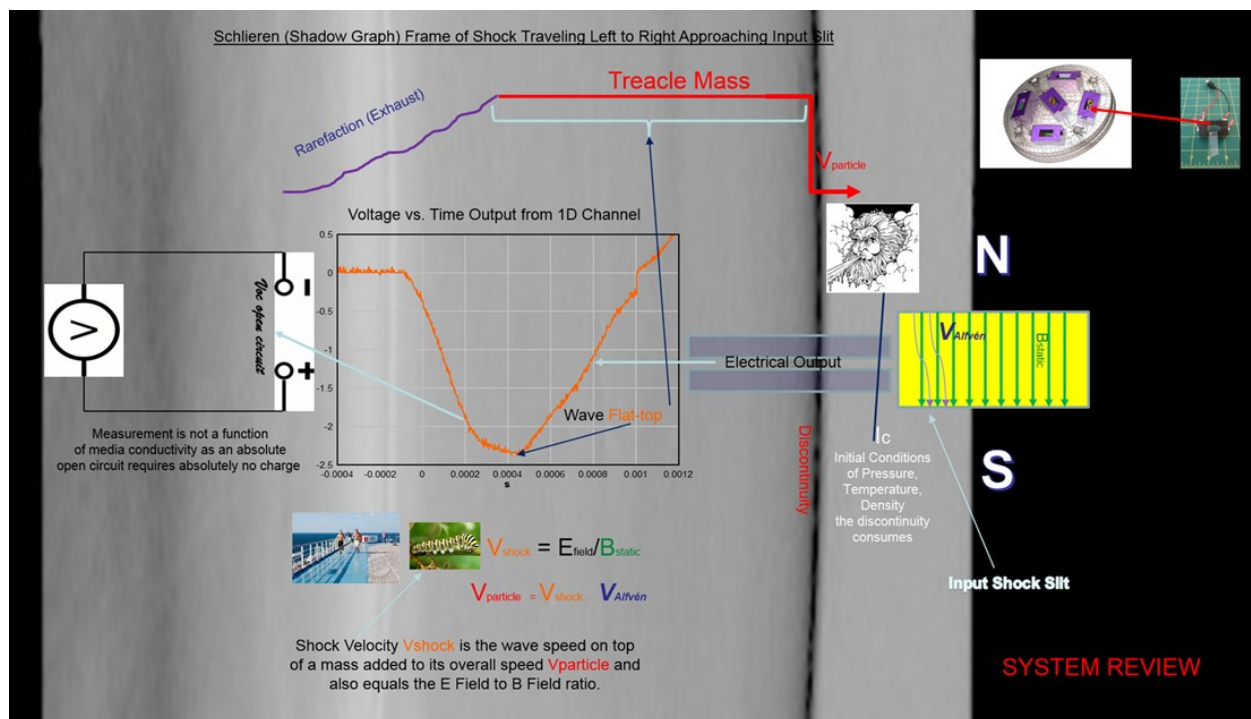


Figure 3-2 System Review

Below is the Laboratory Air Shock test designed to confirm with Schlieren Photography system linearity and quantify the delay between event initiation and event detection with the open circuit voltage measurement.

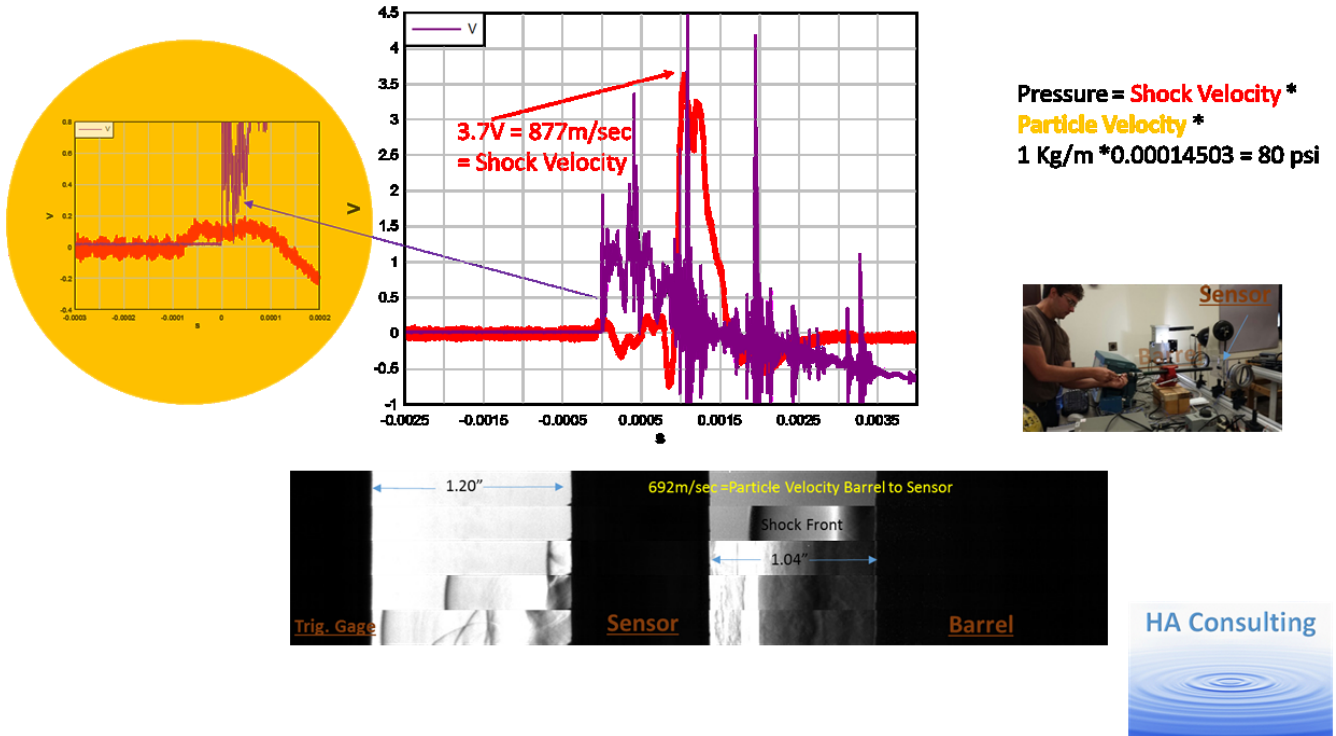


Figure 4-2 - An ~ 700 m/s Air Shock and Schlieren Film

In the above red is the sensor output and purple is the trigger. The Schlieren film below the trace confirms the particle velocity as well as the shock velocity. Pressure was measured independently as 80 psi confirming both the shock and particle velocities. The delay, which is a function of particle velocity, in the above test is ~ 600 microseconds. It will be shown later that the delay at our velocity of interest range is ~200 microseconds.

Below is the Laboratory Helium Shock test designed to increase the shock velocity and confirm with Schlieren photography system linearity, quantify the delay between event initiation and event detection, and delay dependence on velocity with the open circuit voltage measurement.

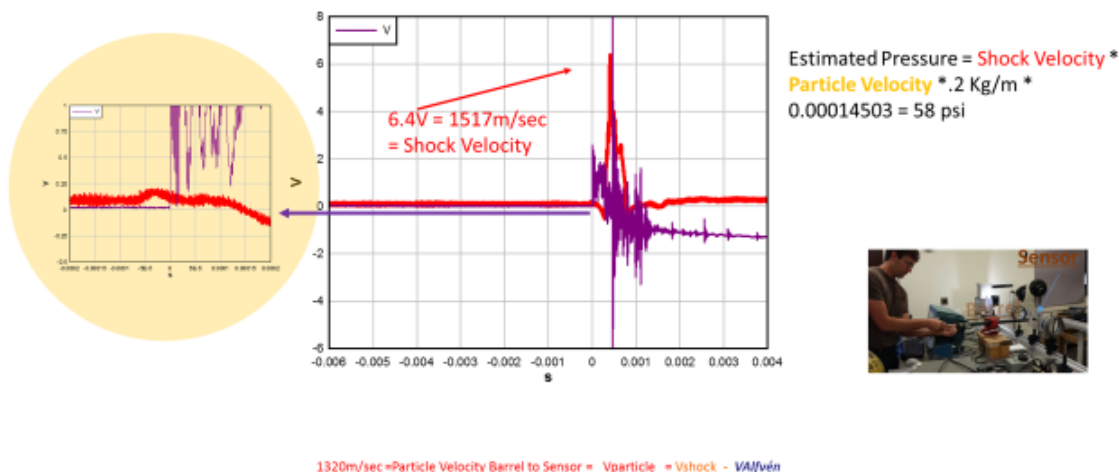


Figure 5-2- An ~ 1500 m/s Helium Shock

In the above red is the sensor output and purple is the trigger. The Schlieren films confirmed the particle velocity as well as the shock velocity. Pressure was measured independently as 60 psi confirming both the shock and particle velocities. The delay, which is a function of particle velocity, in the above test is ~ 300 microseconds. It will be shown later that the delay at our velocity of interest range is ~200 microseconds.

h1. The sensor array was tested at scale 1.5 with the equivalent trigger devices and a defined shock produced by 50#'s of C4 explosive. The results are also shown below.

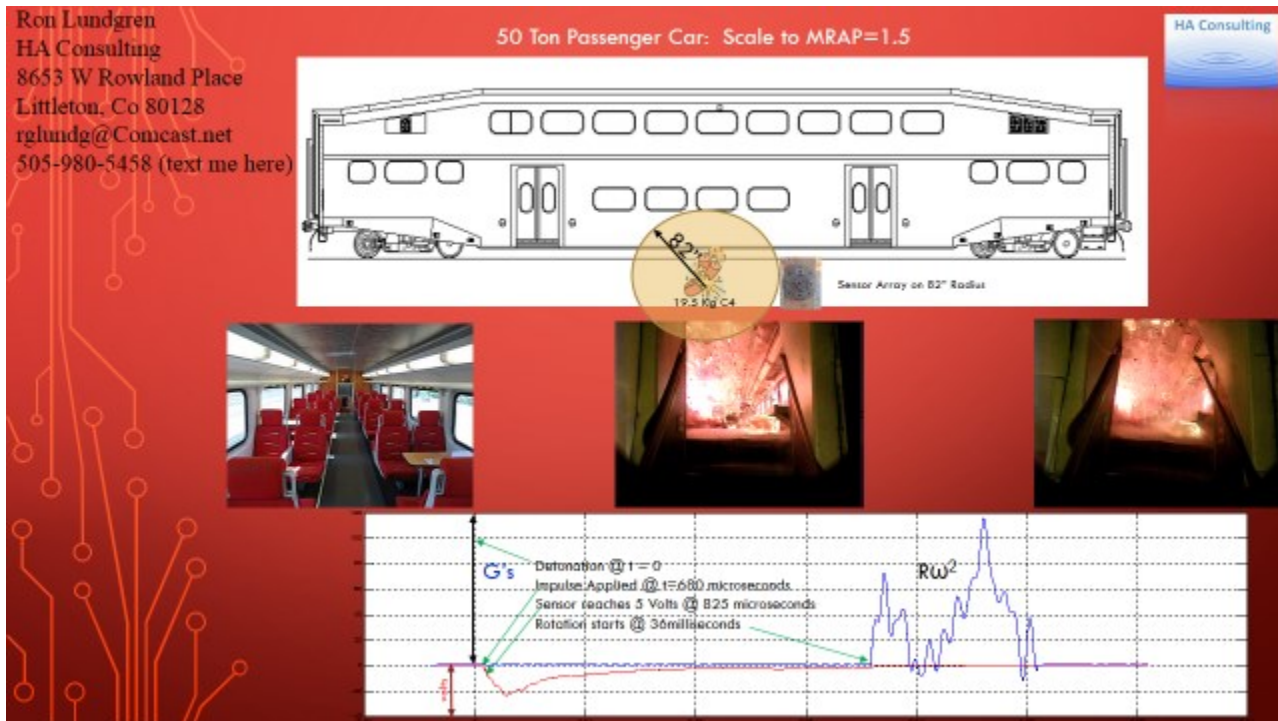


Figure 6-2 - A 1.5 Scaled Test to a MRAP Vehicle

The above test is 50 #'s of C4 Explosive placed 82" from the frame of a 50 Ton Passenger Car. This scales to 1.5 the mass of an MRAP vehicle in explosive weight, distance from detonation, and momentum resistance. T=0 in the graph is the detonation of the explosive. At t= 680 microseconds the initial impulse (the first link in the chain) is applied i.e., the shock has reached the side of the Car. The sensor detects a voltage rise to 5 volts at t=825 microseconds. The difference is 145 microseonds. First movement, which is role in a horizontal test application of momentem i.e.,  $R \cdot \Omega^2$ , is 36 milliseconds as confirmed by the film and the graph showing the sensor in red and the  $R\omega^2$  acceleration in blue.  $\Omega$  ( $\omega$ ) above is the rolling angular velocity of the Car, produced by  $\alpha$  (angular acceleration due to impulse). Angular acceleration was not measured; however since it is orthoganal to the  $R\omega^2$  component it vector addition does not significantly increase the peak G's an occupant would be exposed to.

The sensors were retrieved after the tests and their B fields measured and compared to the B field measurements taken directly before the tests. In all cases the B fields after the test were within 1% of the B fields before the test, which is the error in the measurment. This confirms the robustness of these sensors.

Finally, this test makes unequivocal the assertion that the sensor will sense an explosive event with a minimum delay and with more than sufficient time left to deploy personnel protective devices that null the effects on humans of the deleterious momentum transfer (G loading).

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## Conclusions and Recommendations

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For 3 above, the data is presented in purple. From these results the following conclusions and recommendations associated with 3 for this time period were:

- A. The sensor (voltage output) is linear with applied B field and input fluid (shock) velocity. (Conclusion)
- B. The sensor (voltage output) is not a function of conductivity. This is due to the open circuit nature of the measurement. In the quantum limit an open circuit has infinite resistance and therefore requires 1 over infinity conductivity or one electron.
- C. The sensor delay in signalling an event after application of impulse is ~200 microseconds for an MRAP vehicle. (Conclusion)
- D. Sensor delay to detection is a function of the particle velocity and decreases linearly as the particle velocity of the event increases. (Conclusion)
- E. Measurements of the B Field in a sensor after each application of high shock consistently do not show a change in the B field. Also real time scope measurements confirm the B field does not change during fluid (shock transit). This is another statement of linearity. (Conclusion)
- F. It is unequivocal that the sensor will detect an event of interest in more than sufficient time to deploy personnel protection. (Conclusion) The full movie of this breakthrough test event has been sent under separate cover to TARDEC, Mr. Sebastian K Karwaczynski.
- G. Based on the above it is recommended that the project:
  - a. Proceed with the remainder of tasks e and g and complete task i.
  - b. Exercise the system with the model over the range of possible explosive events an MRAP will be exposed to.
  - c. Test the sensor "Brains" in the Laboratory with air and helium shocks and in the field with 2# explosive charges.

With respect to 4 above, no significant changes have occurred within HA Consulting or its sub-contractor New Mexico Tech (Energetic Materials Research and Test Center) that would effect the performance of this contract; the contract is on schedule.

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# Final Interim Time Period Report

This section is the specific deliverable for the period January 6, 2014 thru March 7, 2014 as specified in Contract W56HZV-13-C-028. It covers the following required deliverables:

1. The work performed to date
2. The work performed against the Statement of Work
3. Technical information regarding the sensor i.e., test data results, positive or negative, to include progress against the ultimate goal (a sensor capable of sensing an event early enough to allow personnel protective devices to be deployed); conclusions derived from the data; feasibility and recommendations.
4. Significant changes to the Contractor's organization; contract schedule status; next period activities.

For 1 and 2 above, the work performed to date measured against the contractual tasks is as follows:

There are 9 tasks a thru i as defined in the contract and listed below. Of the above 9 tasks the first four were completed during the previous 1<sup>st</sup> interim reporting period. Tasks f, and h were completed during the second reporting period and e was completed thru hardware design and detail to include the electrical design and detail portion. Task g, which also includes a model development, is also fully complete. The completed remainders are individually explained below:

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## Statement of Work

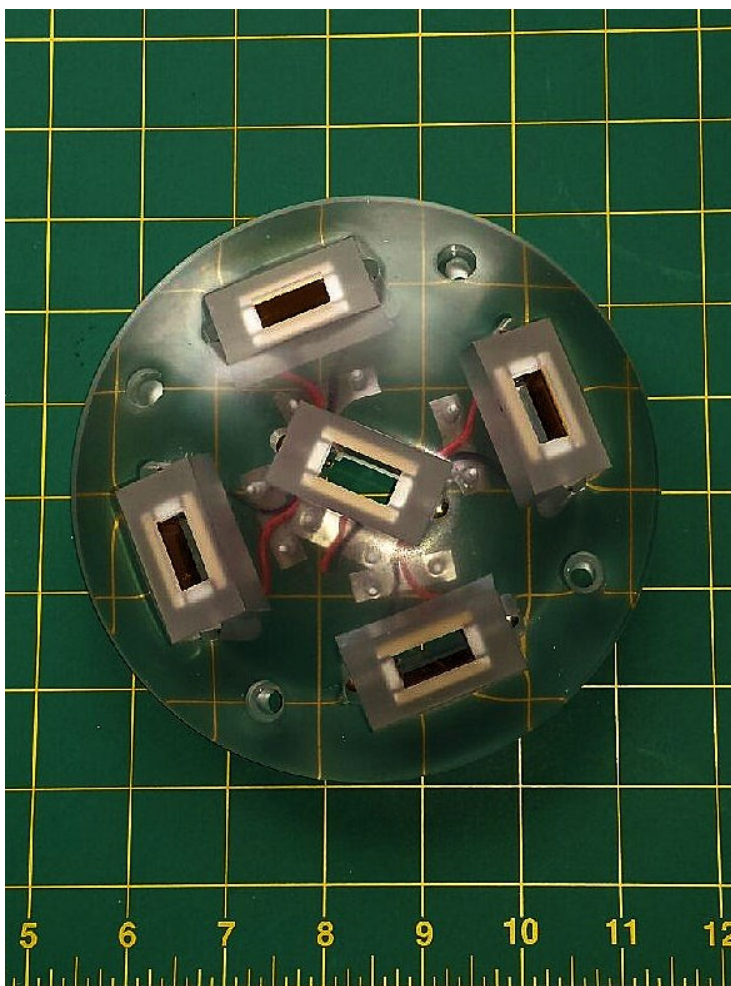
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- a. Define the input required to trigger the protective devices and timing requirements.
  - b. Determine the range of lethal shock velocities that an Underbody will be exposed to.
  - c. Determine placement of the sensor to intercept the shock prior to interaction with the carriage.
  - d. Size the Magnetic B Field, and conductive pick-up terminal spacing to accommodate 1 above.
  - e. Design and detail the sensor.
  - f. Build prototypes for evaluation testing. Estimate 5 prototypes.
  - g. Test prototypes with defined shocks and evaluate the output with Schlieren photography and data recorders. Estimate 10 shock tests to fully characterize an array.
  - h. Connect sensor array to protective devices and trigger devices with defined shocks in 2 above.
  - i. Prepare the Scientific and Technical Report.
-

## Statement of Work Performance

Of the above g tasks the first four were completed during the 1<sup>st</sup> interim reporting period. Tasks **f**, and **h** were totally completed during the second reporting period and **e** was 80% complete and **g** was 50% complete. This report in total completes Task **i**. The remainder of **e** and **g** were completed as follows:

- e. Once the Tesla formulation ( $V=uB_0d$  where **V**=open circuit voltage; **B<sub>0</sub>**=Magnetic Field in Teslas; **d**=spacing between pickup terminals and **u** the velocity of the input shock fluid) was verified to be linear and not a function of conductivity during the 1<sup>st</sup> interim, the design was finalized with only minor dimensional changes. The final result is shown below:

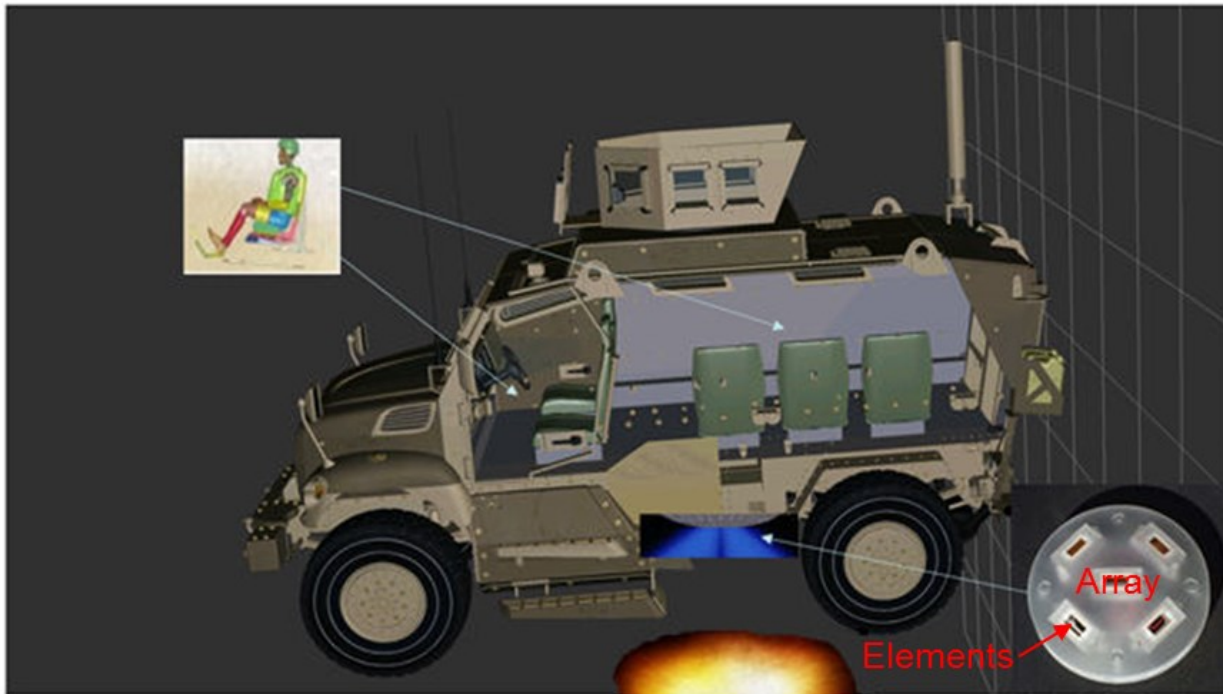


*Figures 1-3 Final Configuration of Test Sensor and Array*

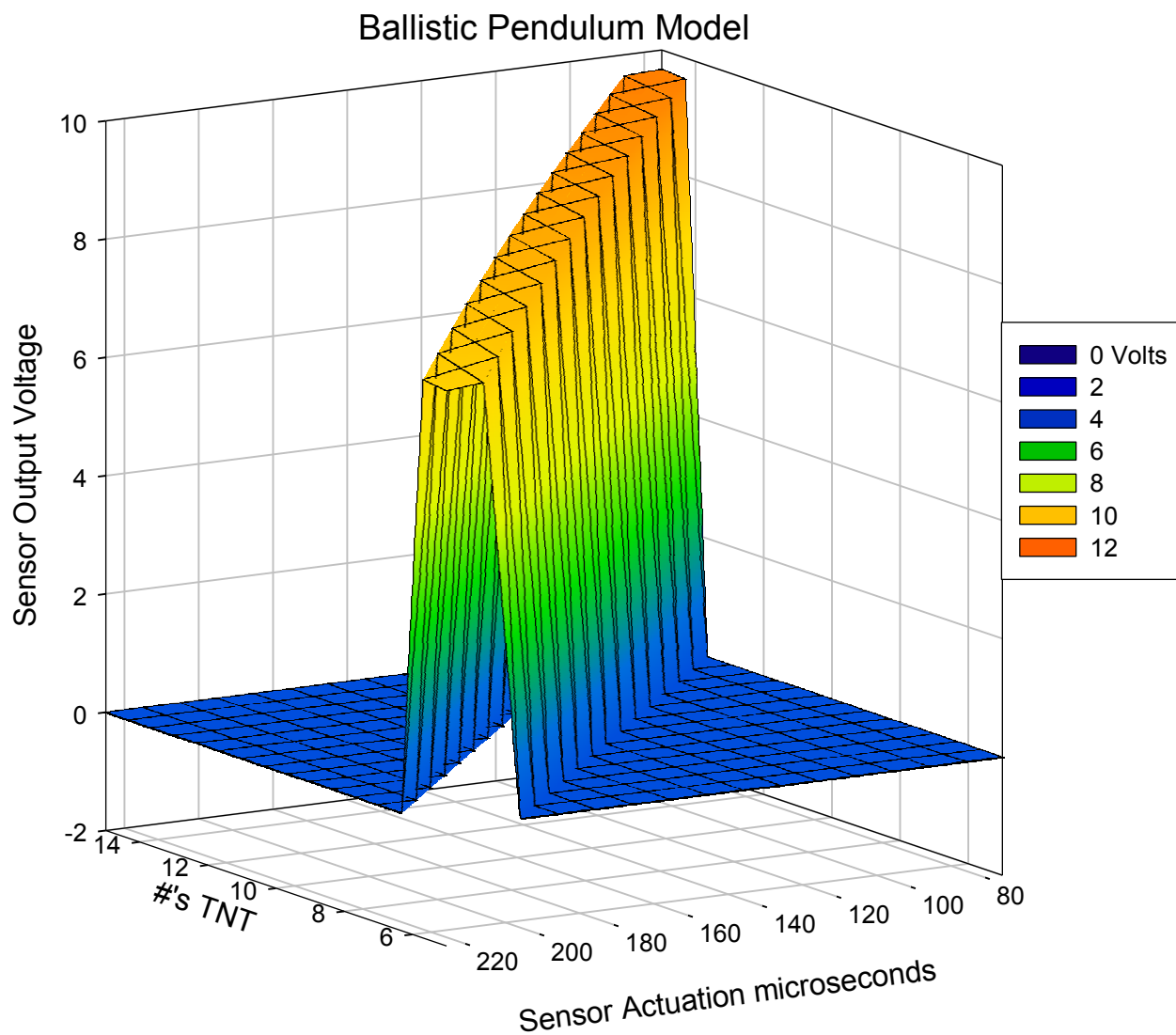
The remainder of the electrical work consisted of measuring canted shock inputs to the sensor to confirm the cosine effect to confirm adequate sensor coverage geometry for the underbody and finally estimating its power output again to confirm proper geometry and sizing. These are described below in the Empirical Data Section.

- g. Final electrical confidence tests at scale were conducted. Additionally the sensor internal resistance was evaluated. The prototype outputs were fully characterized and tested at scale (10 – 15 # TNT equivalent) and the results evaluated with data recorders. The results are shown in the Empirical Data section below. The model was written and exercised over the range of 10 – 15 # TNT equivalent and shown directly below:

A ballistic pendulum model was used where the center of pressure of the event is defined as a longitudinal radius arm of 8' from the rotation point. This rotation point was defined as the front axial

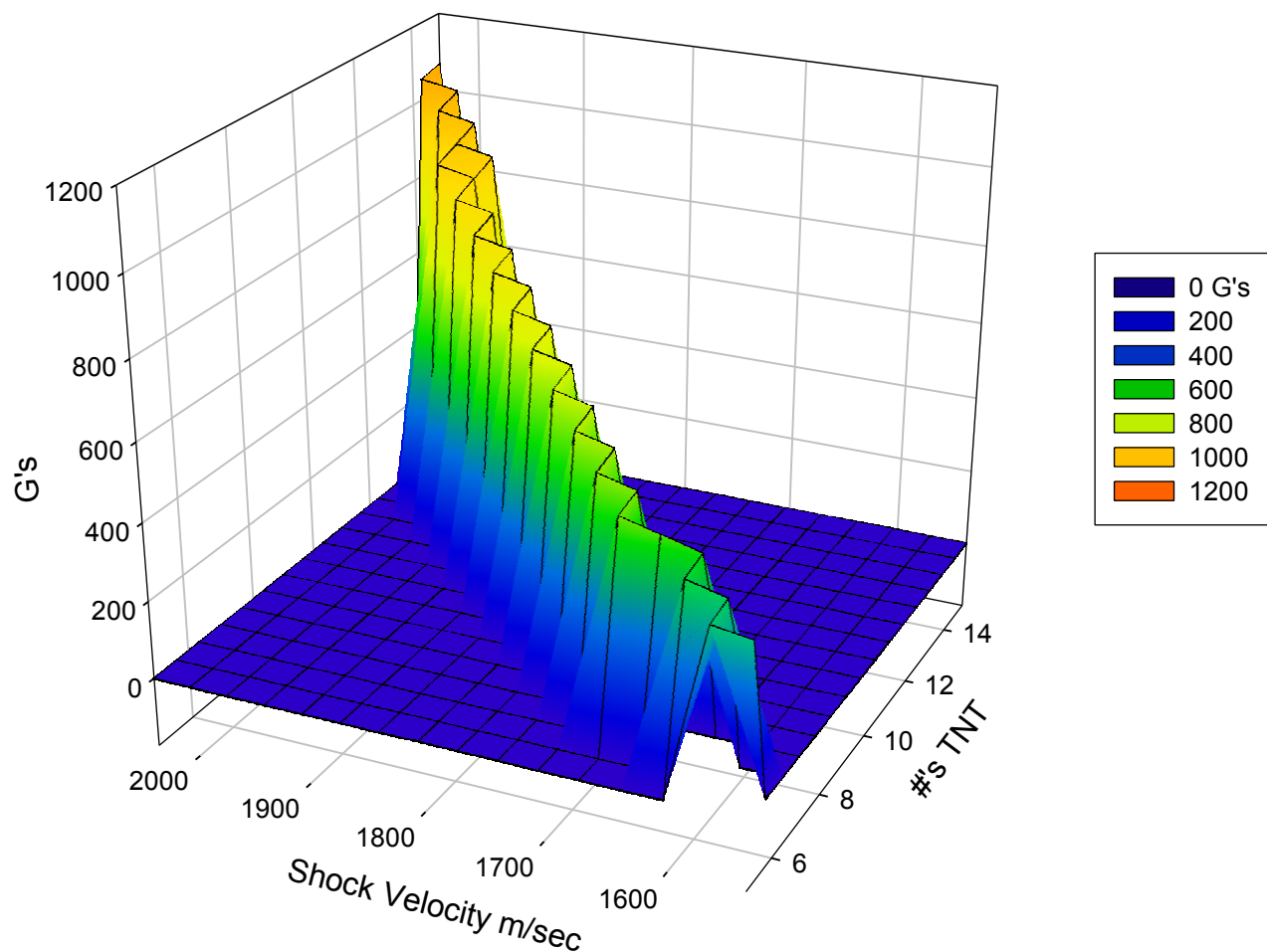


*Figures 2-3 Ballistic Pendulum with Center of Pressure at 8' Longitudinally from the Front Axel*



*Figures 3-3 Ballistic Pendulum Model Sensor Actuation and Output Voltage versus # TNT*

## MRAP Ballistic Pendulum Model



*Figures 4-3 Ballistic Pendulum Model Input Shock Velocity and Output G load versus #s TNT*

- i. This report in its entirety completes Task i

## Empirical Data

### e. Design and detail the sensor - Confirmation of Geometry

The test input below was an orthogonal helium shock (velocity – 1650meters/sec) plane into the sensor element. The figure shows three frames of the Schlieren (shadow-graph) video that confirms the input shock planes geometry and velocity.

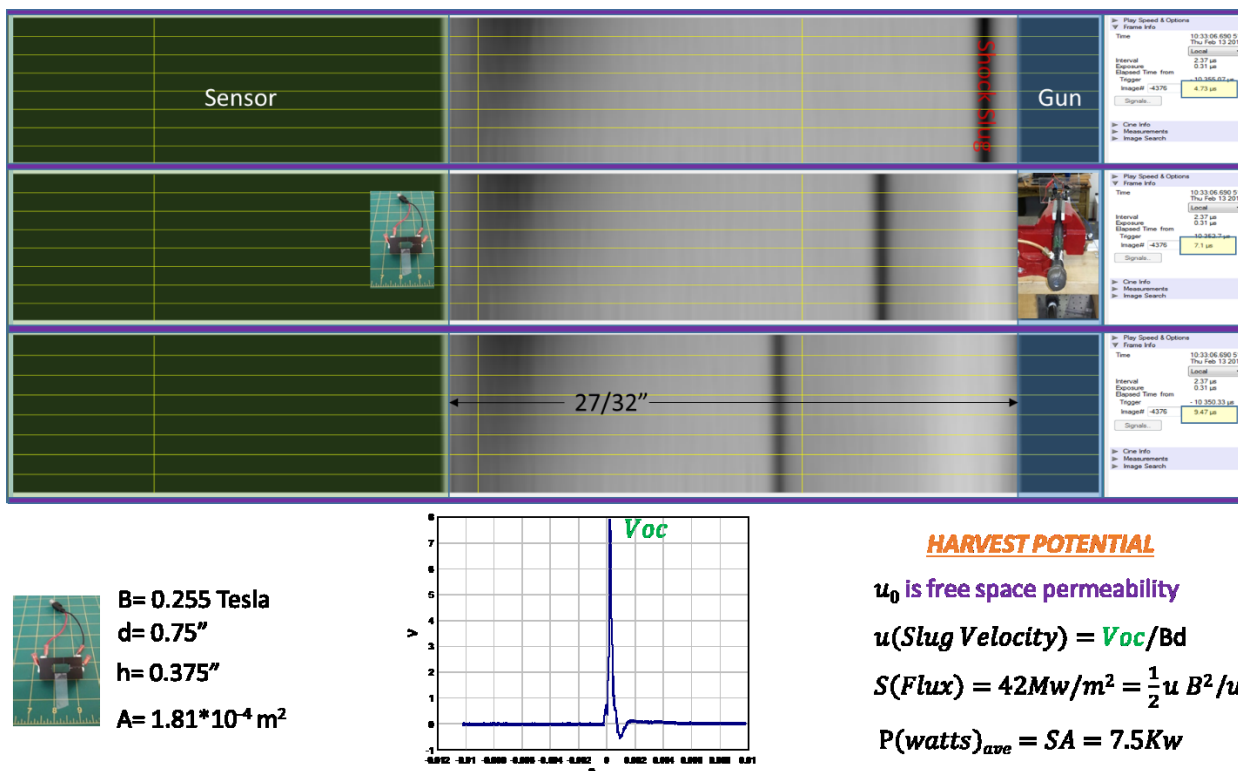


Figure 5-3 Orthogonal Helium Shock Input Orthogonal to Sensor Element - V=7.8volts

The test of the above Figure 5-3 was repeated this time with a canted shock front. A surprising result from the test showed that canted shocks result in constructive signal interference. The benefit is that the sensor set point will not have to be adjusted for canted input shock planes.

Note that the lower right hand section of the two figures compute the system flux available (Poynting Vector) and indicate sufficient power available to direct drive (no additional power source other than the sensor itself) a gas generator or explosive actuator.

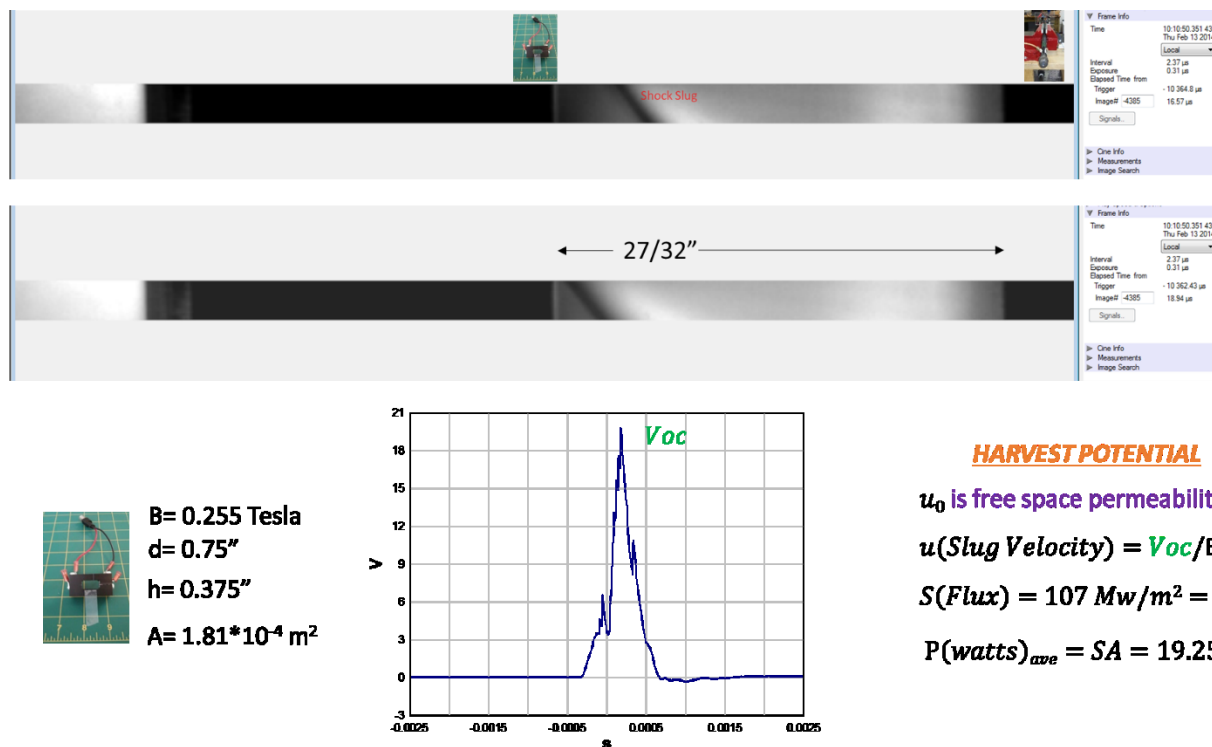


Figure 6-3 - Canted (40°) Helium Shock Input to Sensor Element - V=6.1

g. Test prototypes with defined shocks and evaluate the output

To fully evaluate the sensor and array the internal resistance of an air shock was determined. An air shock was used as this is the media in front of the shock for an event of interest. The red trace is the air shock open circuit output into a scope. The blue trace is the output when a 9200 microfarad capacitor is placed in the circuit. The method allows the delay between traces to be used to calculate the RC time constant of the circuit since only R internal is unknown. The circuit was modeled in electrical circuit model software SPICE, shown below, to calculate the value of the internal Resistance. The result is 85 milliohms of internal resistance in the input air shock.

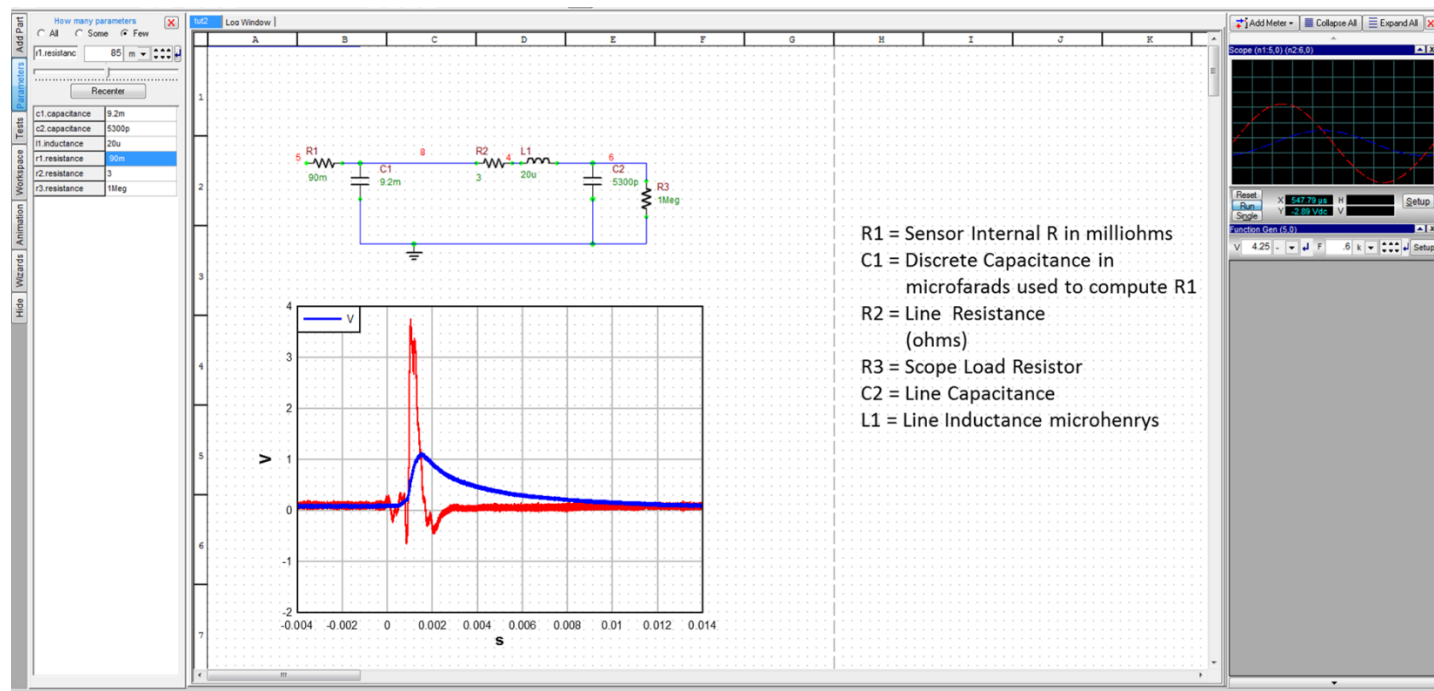


Figure 7-3 - Test Circuit and SPICE model to determine Internal Impedance of an Air Shock

A final confidence test was conducted to fully complete Task g. The test was a cased explosive full scale event of ~12# TNT equivalent. The results were excellent and shown below. Additionally the sensor's ability to determine dynamic pressure was demonstrated.

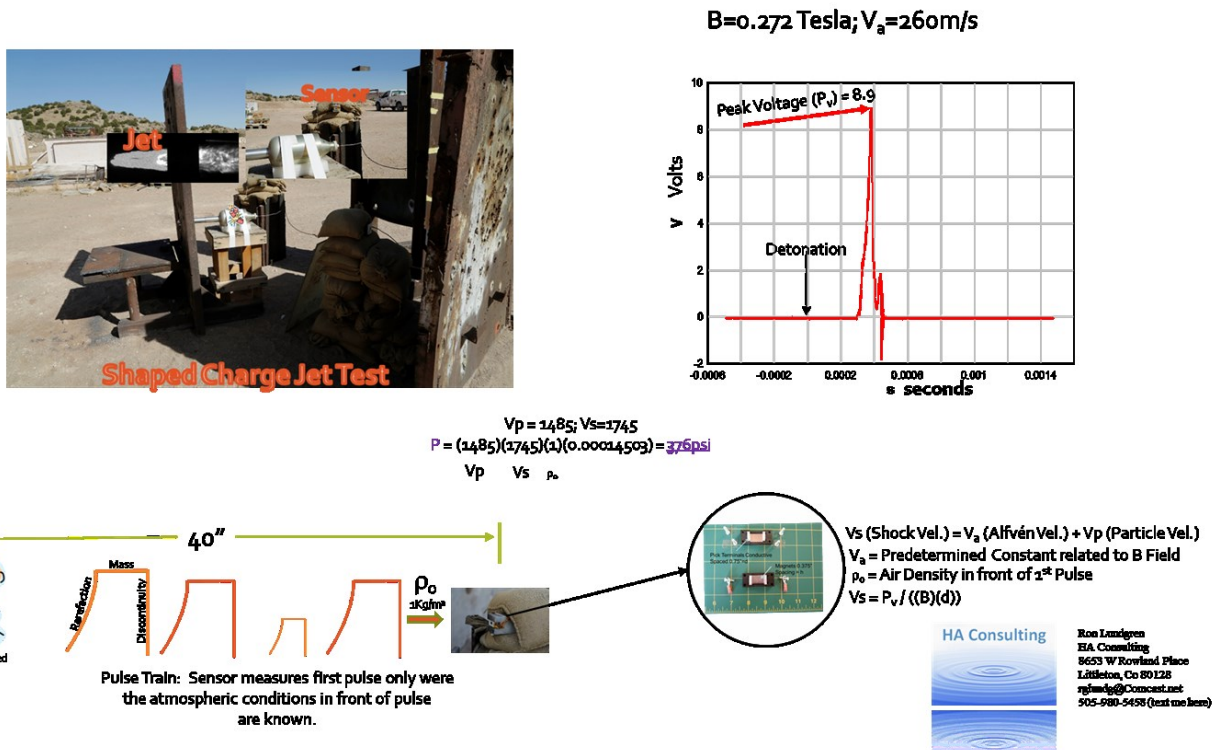


Figure 8-3 - Final Confidence Test with 12# TNT Equivalent

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## Final Conclusions and Recommendations

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From the total effort of Phase I the final conclusions and recommendations are:

- A. The sensor (open circuit voltage output) is linear with the applied magnetic (B) field and input fluid (shock) velocity. (Conclusion)
  - B. Measurements of the B Field in a sensor after each application of high shock consistently do not show a change in the B field. Real time scope measurements confirm the B field does not change during fluid (shock transit). This is another statement of linearity. (Conclusion)
  - C. The sensor (voltage output) is not a function of conductivity. This is due to the open circuit nature of the measurement. In the quantum limit an open circuit has infinite resistance and therefore requires  $1$  over infinity conductivity or one electron. (Conclusion)
  - D. Based on C above it is recommended that open circuit voltage output be used to detect the events of interest by acting to deploy safety systems when the voltage reaches 4 volts which indicates a Mach Number of 2.85. (Recommendation)
  - E. For entry velocities above Mach 1 the signal is positive going with respect to the negative and grounded terminal as determined by the right hand rule. (Conclusion)
  - F. The chaos in the fireball does not effect any conclusions, rather works to the advantage of deployment of protective devices by annunciating a biologically damaging event prior to  $t=0$ . (Conclusion)
  - G. The sensor measures the first link in the pulse train, thereby sensing an event before  $t=0$ . The sensor delay in signalling an event after application of first impulse is ~150 microseconds at 10# of TNT equivalent for an MRAP vehicle. (Conclusion)
  - H. Sensor delay to detection is a function of the particle velocity and decreases linearly as the particle velocity (Mach Number) of the event increases. (Conclusion)
  - I. It is unequivocal, as shown in Figure 6.2, that the sensor will detect an event of interest in more than sufficient time to deploy personnel protection. (Conclusion) The full movie of this breakthrough test event has been sent under separate cover to TARDEC, Mr. Sebastian K Karwaczynski.
  - J. For this sensor the measured Flux Density is ~ 100 Mwatts/m<sup>2</sup> and internal resistance of an air shock is ~100 milliohms. (Conclusion)
  - K. Based on J. above it is recommended that the sensor direct drive safety system's gas generators or explosive actuators with event energy. (Recommendation)
-

- L. The sensor as constructed and demonstrated provides a readily additional benefit of a first alert feature for other military services that will signal or call for help during a damaging event to equipment and/or personnel. It is recommended that consideration be given to utilizing the sensor in this manner. (Recommendation)
  
- M. The sensor output waveform was demonstrated in Phase I to detect and accurately measure the blast velocity and dynamic pressure in an explosive event. This allows the sensor as constructed and demonstrated to provide the additional benefit of a signal of proper weapon function for target damage assessment applications for Army/Navy indirect fire and Air Force bombing missions. It is recommended that consideration be given to utilizing the sensor in this manner. (Recommendation)
  
- N. A derivative of the Phase I demonstrated technology could provide next generation hearing protection for combat soldiers, modifying the Phase I sensor by; scaling the geometry of the device to fit the human ear and attaching dropping resistors to harmlessly dissipate the blast energy as heat and protect combat personnel exposed to a shock blast from internal ear damage, but still allowing cognizance of normal sound, and commercially applicable to hunters, fire and police departments as well as Cochlear implant patients. It is recommended that additional investigation be undertaken to determine the feasibility of such a derivative. (Recommendation)